Status and plan of IHEP CMS physics analyses in ZZ channel

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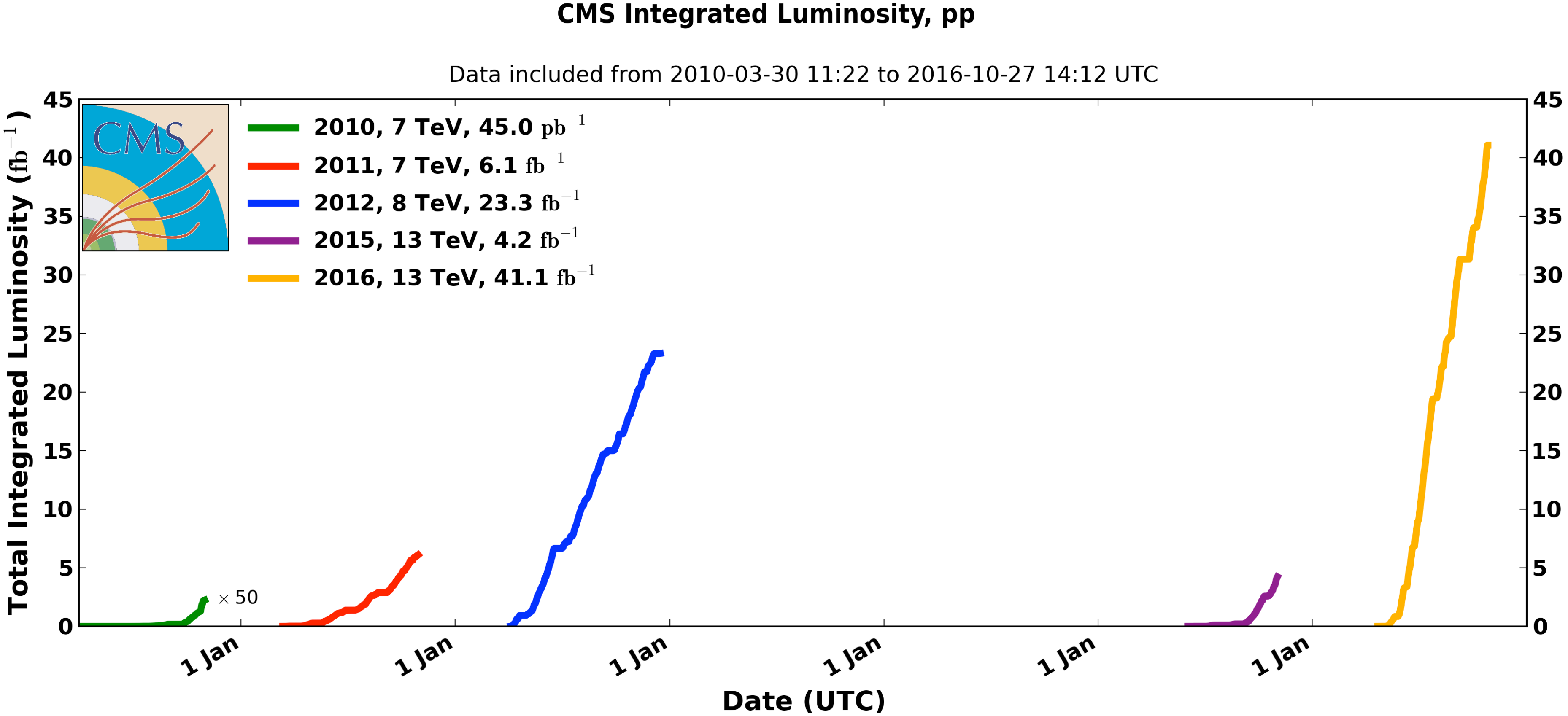
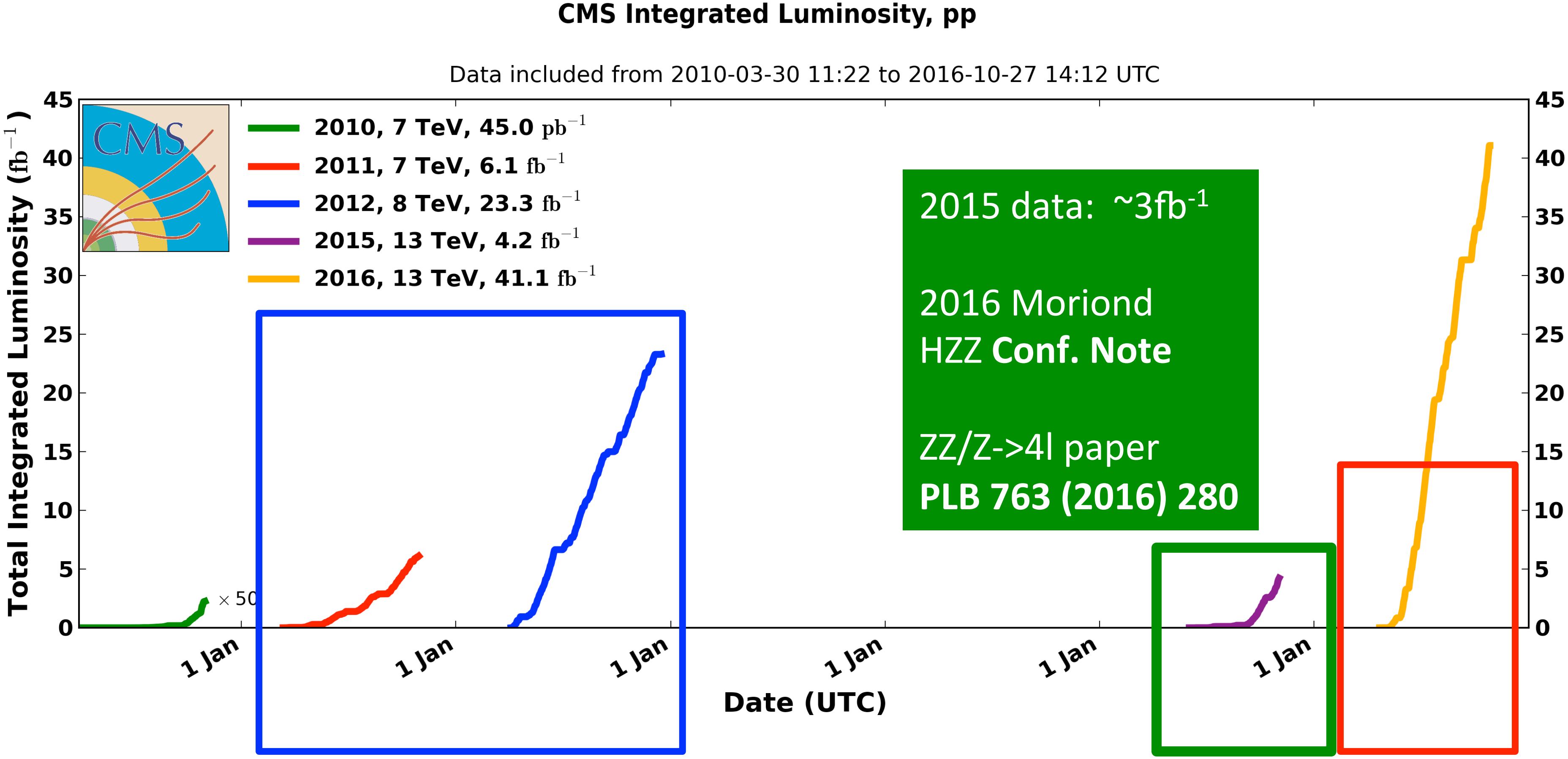
Nov. 18, 2016

CMS Run 2 data taking



LHC finished 2016 pp run in October, delivered 41 fb^{-1} to CMS and ~37 fb^{-1} recorded, ~35 fb^{-1} good data for physics analysis

CMS Run 2 data taking



2015 data: $\sim 3fb^{-1}$

2016 Moriond
HZZ **Conf. Note**

ZZ/Z->4l paper
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Run I data:
Higgs cross section measurements
published in **JHEP 1604 (2016) 005**

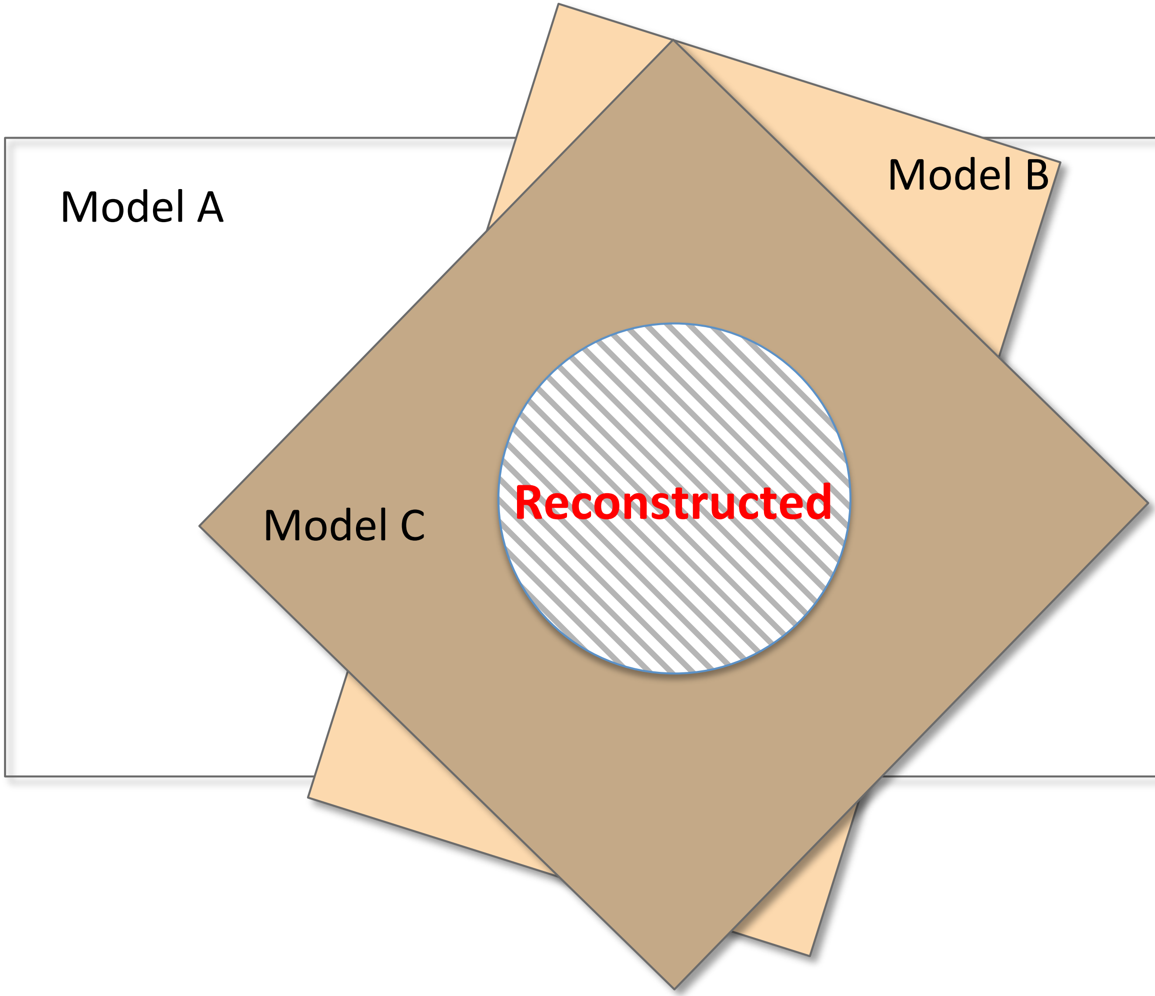
2016 data: $\sim 13fb^{-1}$
2016 ICHEP
HZZ **Conf. Note**

Fiducial cross section

- An important property to measure of the discovered Higgs boson is its (differential) fiducial cross section
  - Important test of SM predictions and probe of BSM effects
- To minimize model dependence
  - The measurement is performed in a fiducial phase space close to experimental acceptance
  - Fiducial space definition can be reproduced by theorists/phenomenologists

Fiducial cross section

- Acceptance has a strong model dependence, e.g. between SM production modes by up to 60%



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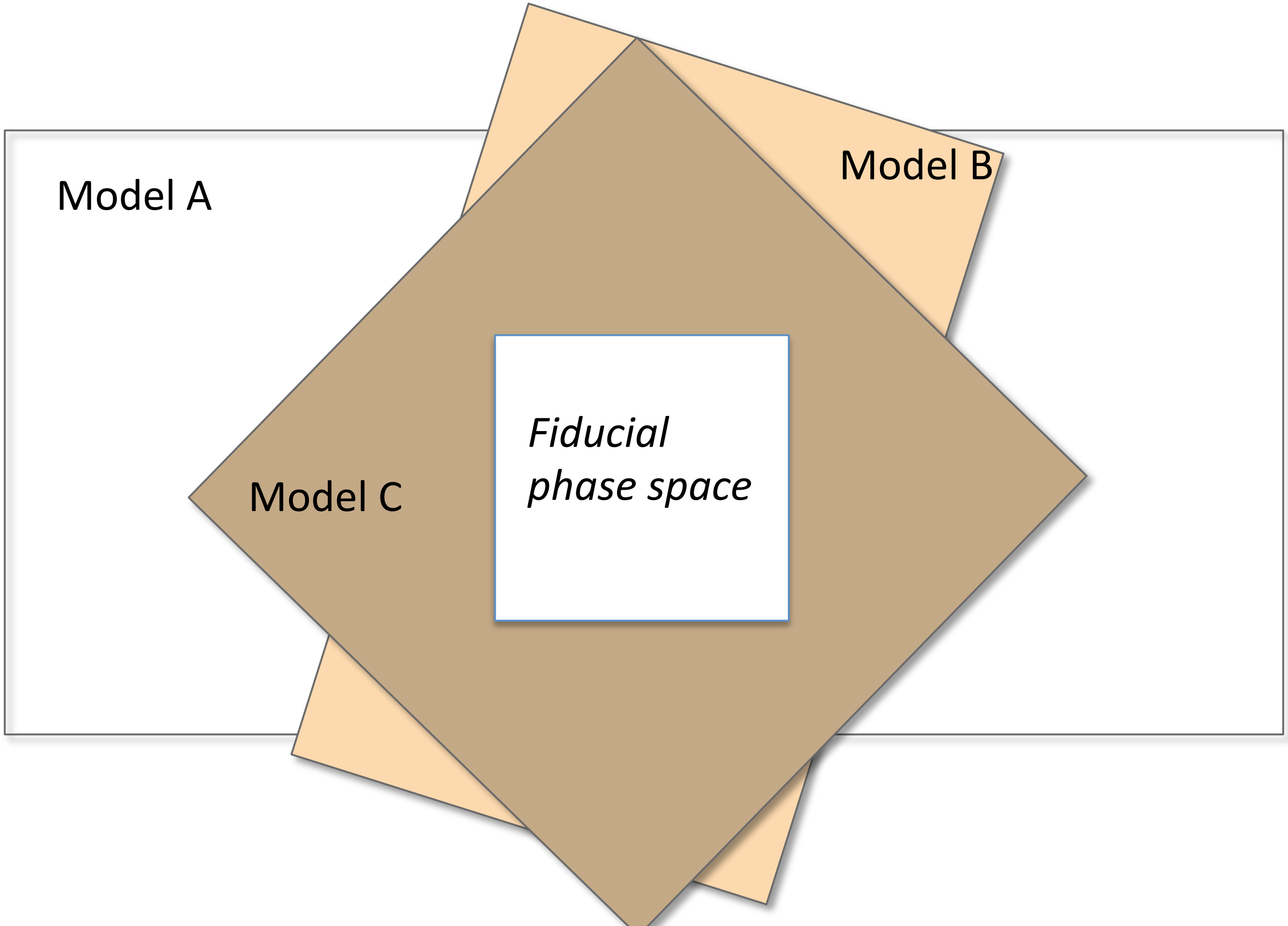

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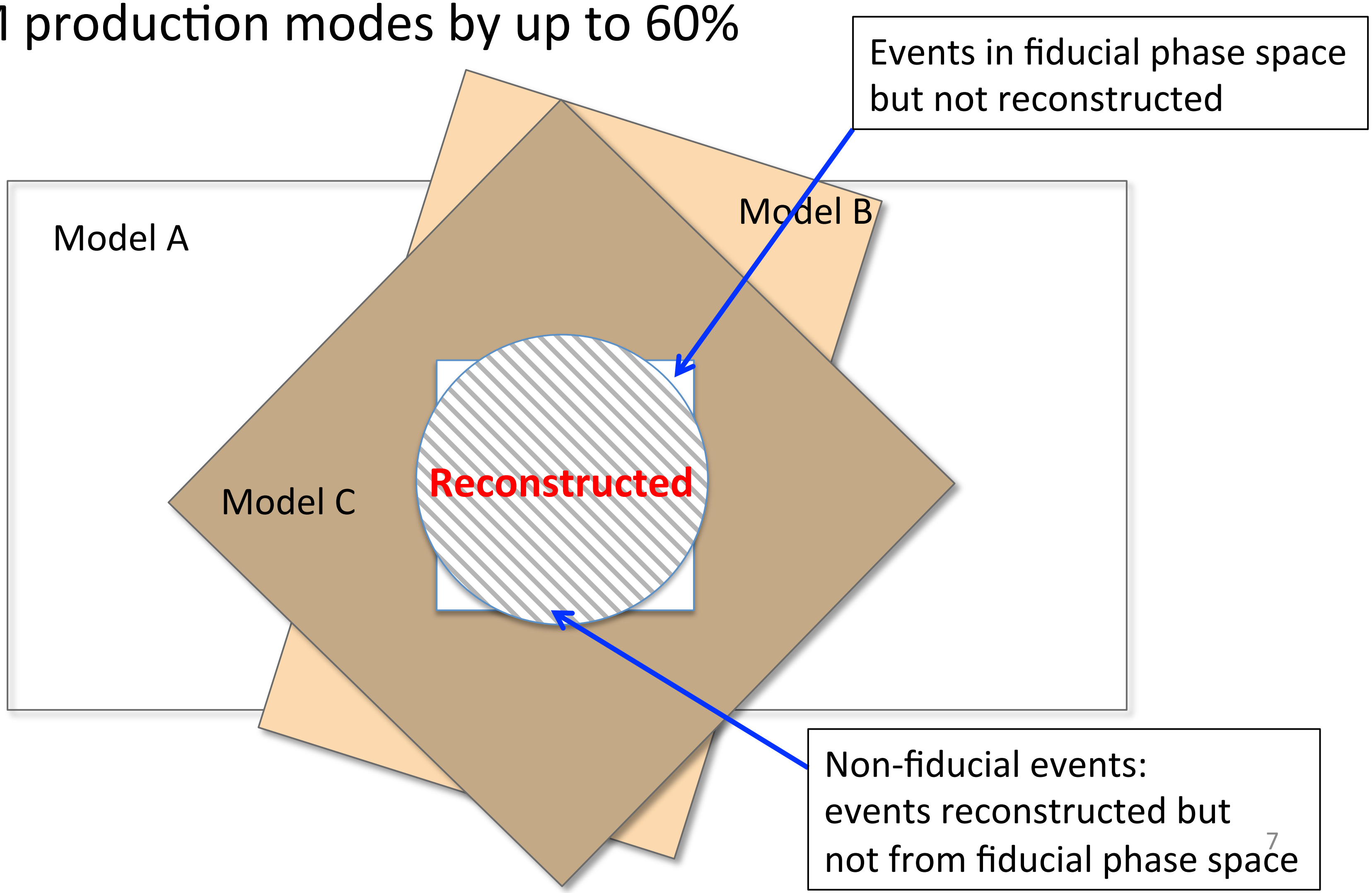
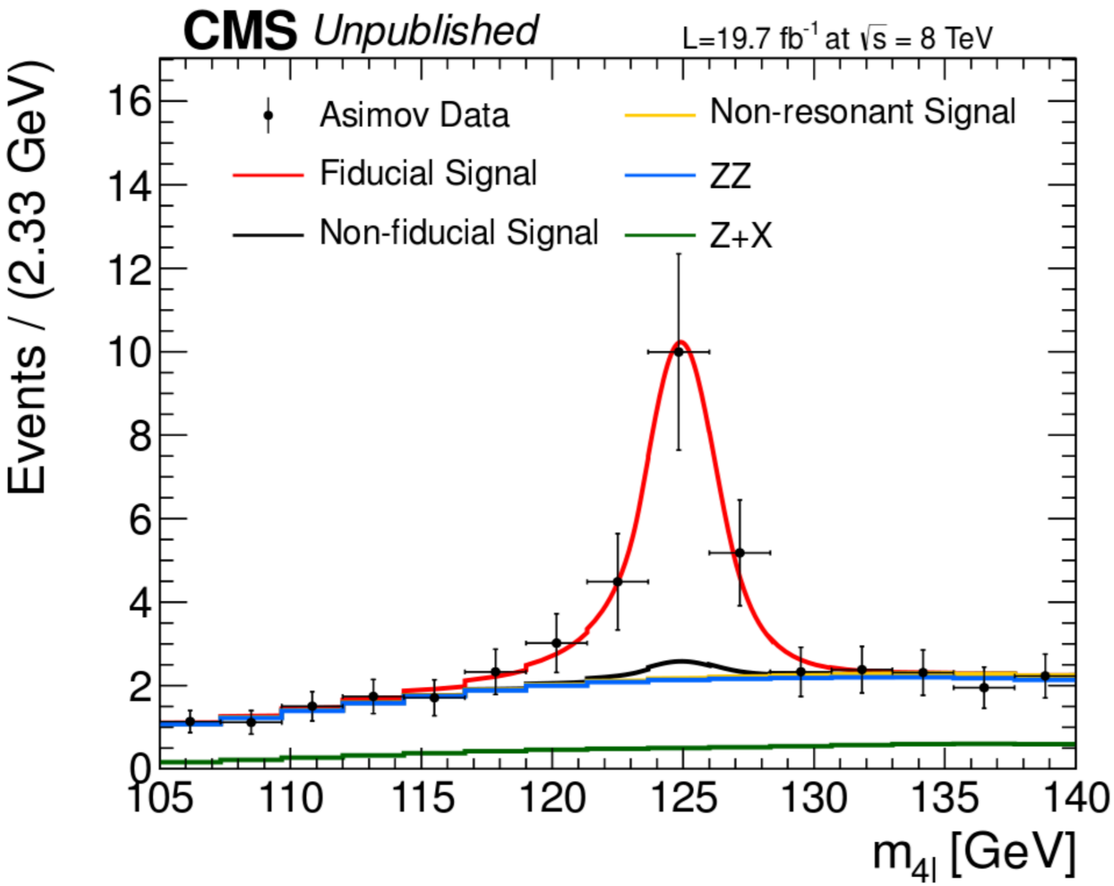


Fiducial phase space definition

Requirements for the $\mathrm{H} \rightarrow 4\ell$ fiducial phase space	
Lepton kinematics and isolation	
Leading lepton p_T	$p_T > 20$ GeV
Sub-leading lepton p_T	$p_T > 10$ GeV
Additional electrons (muons) p_T	$p_T > 7$ (5) GeV
Pseudorapidity of electrons (muons)	$\lvert\eta\rvert < 2.5$ (2.4)
p_T Sum of all stable particles within $\Delta R < 0.4$ from lepton	less than $0.4 \cdot p_T$
Event topology	
Existence of at least two SFOS lepton pairs, where leptons satisfy criteria above	
Inv. mass of the Z_1 candidate	$40 < m(Z_1) < 120$ GeV
Inv. mass of the Z_2 candidate	$12 < m(Z_2) < 120$ GeV
Distance between selected four leptons	$\Delta R(\ell_i \ell_j) > 0.02$, for any $i \neq j$
Inv. mass of any opposite-sign lepton pair	$m(\ell_i^+ \ell_j^-) > 4$ GeV, for any $i \neq j$
Inv. mass of the selected four leptons	$105 < m_{4\ell} < 140$ GeV

- A crucial point is the inclusion of isolation in the fiducial selection
  - Does not include neutrinos or FSR photons
  - without isolation, the difference in efficiency between production modes can be more than 50%

Analysis strategy



- **Fiducial Signal Shape*: Double Sided Crystal Ball***
- **"Non-Fiducial" Signal shape: Same as fiducial shape**
  - **fraction of fiducial signal (f_{nonfid})**
  - **fraction depends on model**
- **"Non-resonant" Signal Shape**
  - **One or more leptons not directly from H decay (e.g. WH, ZH, ttH)**
  - **shape constrained from simulation**
- **qqZZ,ggZZ shape and norm from MC**
- **Z+X shape and norm from control regions in data**

$$N_{\rm obs}^{{\rm f},i}(m_{4\ell}) = N_{\rm fid}^{{\rm f},i}(m_{4\ell}) + N_{\rm nonres}^{{\rm f},i}(m_{4\ell}) + N_{\rm nonfid}^{{\rm f},i}(m_{4\ell}) + N_{\rm bkg}^{{\rm f},i}(m_{4\ell})$$

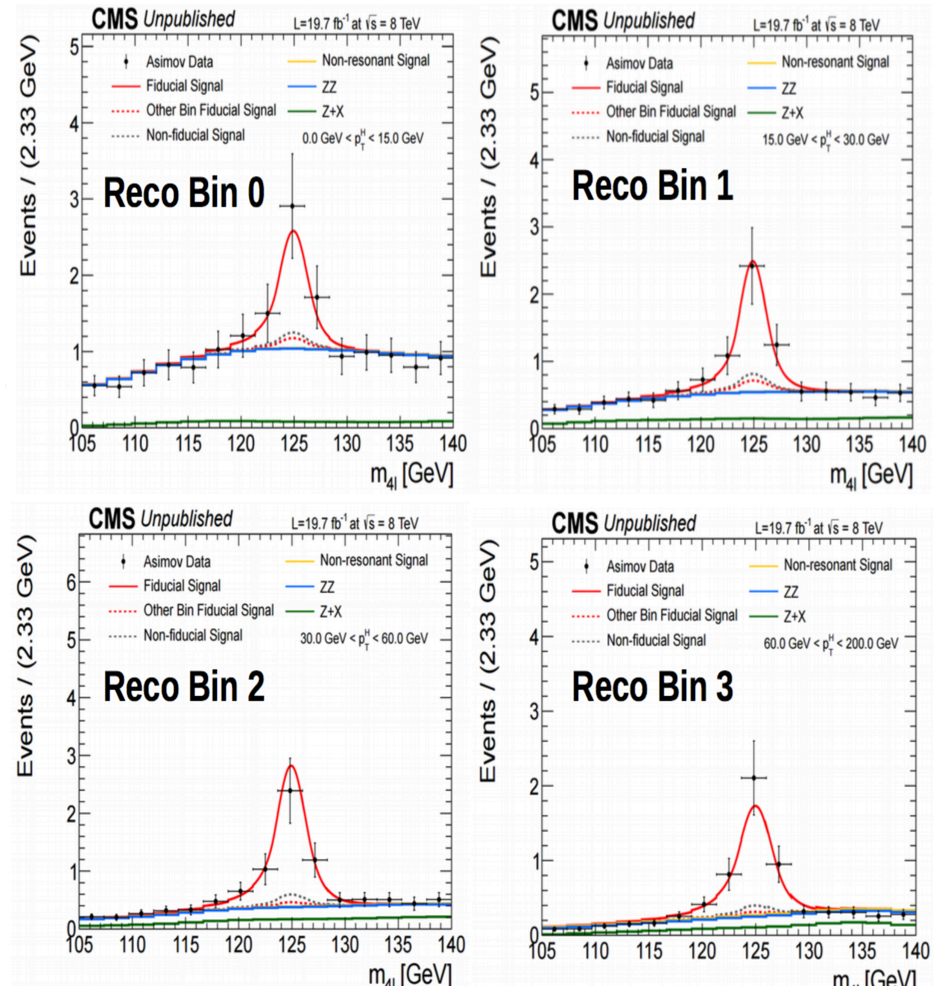
$$= \left(1 + f_{\rm nonfid}^{{\rm f},i}\right) \cdot \sigma_{\rm fid}^{{\rm f},j} \cdot \epsilon_{i,j}^{\rm f} \cdot \mathcal{L} \cdot \mathcal{P}_{\rm res}(m_{4\ell})$$

$$+ N_{\rm nonres}^{{\rm f},i} \cdot \mathcal{P}_{\rm nonres}(m_{4\ell}) + N_{\rm bkg}^{{\rm f},i} \cdot \mathcal{P}_{\rm bkg}(m_{4\ell}),$$

f = final state
i = observable bin at reco level

Fitting/Unfolding procedure

- **Simulataneous fit** of 4 differential bins and 3 final states (=12 channels) per differential measurement
- **1 POI (σ_{fid}) per bin** controls the normalization of the "Fiducial Signal" components
- 2 additional parameters per bin to **float the fractions of each final state**
- **Fiducial signal** from a particular differential bin at fiducial level **can contribute to all differential bins** at reconstruction level
  - controlled by the **detector response matrix (built in the likelihood)**
- **Mass is fixed to 125.0 GeV**



Example fits $p_T(4l)$

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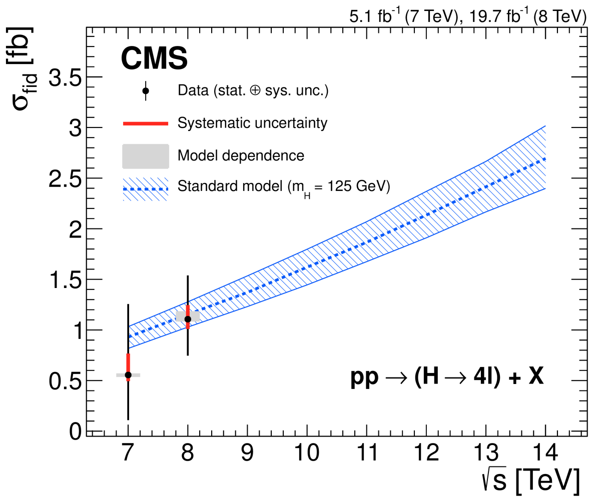
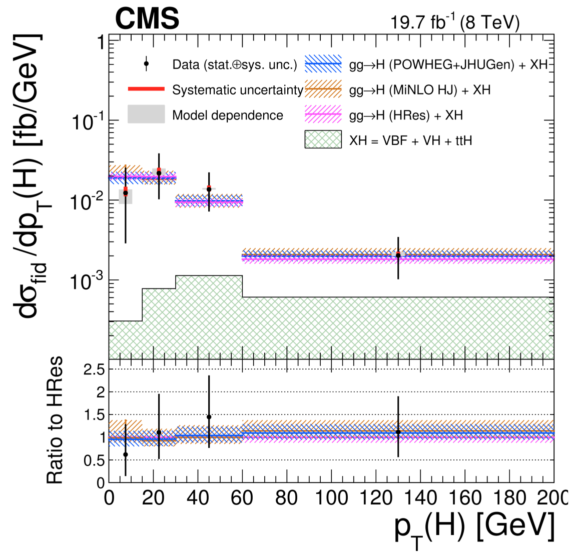
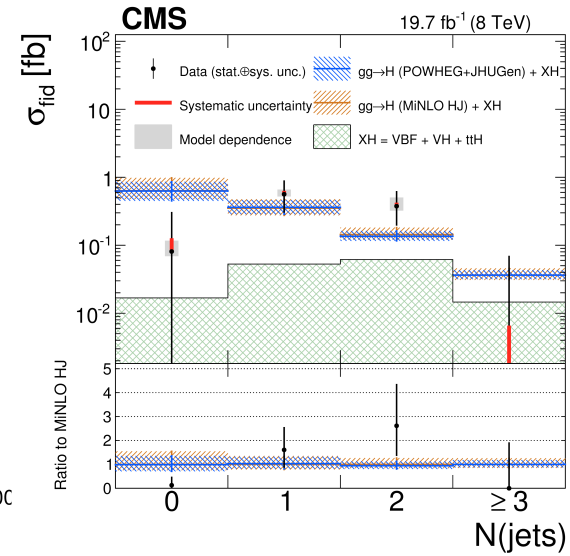
Fiducial XS: Run I results





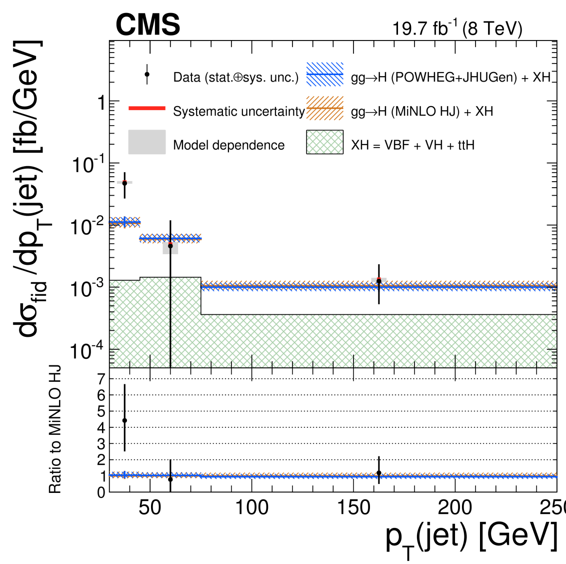


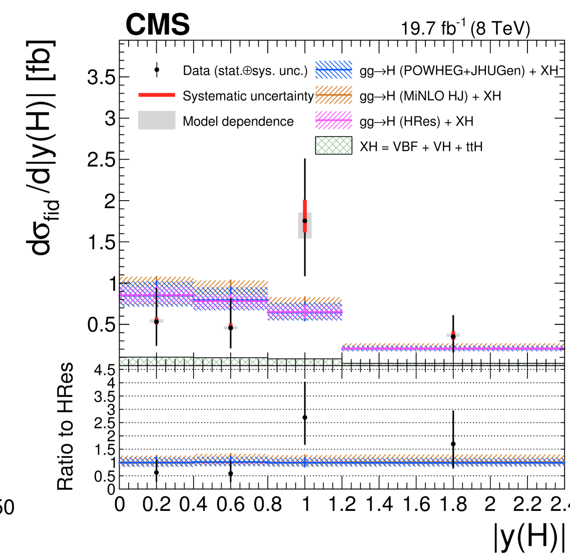
Fiducial cross section $H \to 4\ell$ at 7 TeV	
Measured	$0.56^{+0.67}_{-0.44}$ (stat) $^{+0.21}_{-0.06}$ (syst) ± 0.02 (model) fb
$gg \to H$(HRes) + XH	$0.93^{+0.10}_{-0.11}$ fb
Fiducial cross section $H \to 4\ell$ at 8 TeV	
Measured	$1.11^{+0.41}_{-0.35}$ (stat) $^{+0.14}_{-0.10}$ (syst) $^{+0.08}_{-0.02}$ (model) fb
$gg \to H$(HRes) + XH	$1.15^{+0.12}_{-0.13}$ fb
Ratio of $H \to 4\ell$ fiducial cross sections at 7 and 8 TeV	
Measured	$0.51^{+0.71}_{-0.40}$ (stat) $^{+0.13}_{-0.05}$ (syst) $^{+0.00}_{-0.03}$ (model)
$gg \to H$(HRes) + XH	$0.805^{+0.003}_{-0.010}$

Ratio

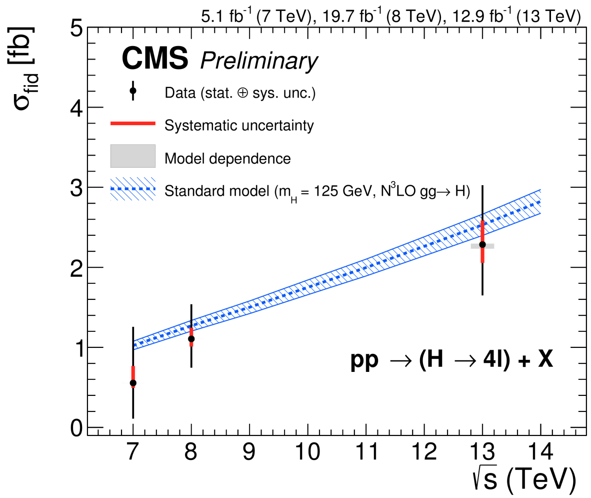
Fiducial cross section $Z \to 4\ell$ at 8 TeV ($50 < m_{4\ell} < 105$ GeV)	
Measured	$4.81^{+0.69}_{-0.63}$ (stat) $^{+0.18}_{-0.19}$ (syst) fb
Powheg	4.56 ± 0.19 fb
Ratio of fiducial cross sections of $H \to 4\ell$ and $Z \to 4\ell$ at 8 TeV ($50 < m_{4\ell} < 140$ GeV)	
Measured	$0.21^{+0.09}_{-0.07}$ (stat) ± 0.01 (syst)
$gg \to H$(HRes) + XH and $Z \to 4\ell$ (Powheg)	0.25 ± 0.04

Z->4l

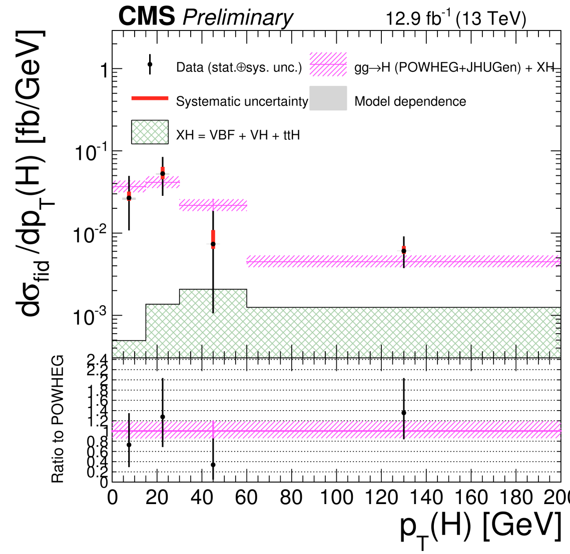


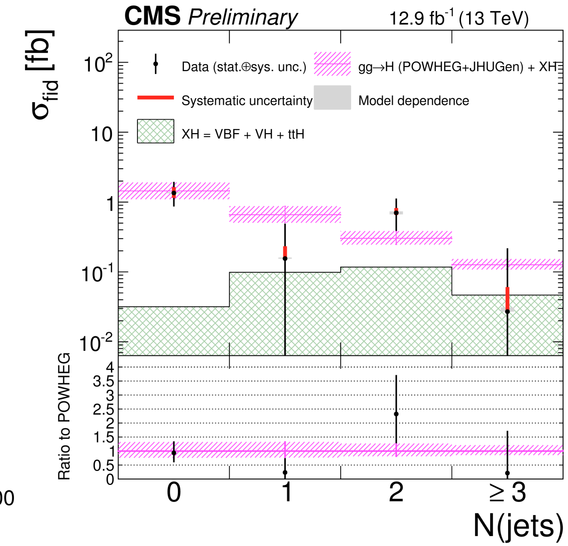


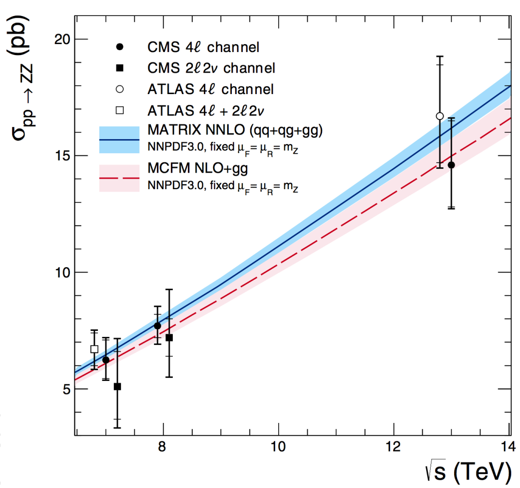
Fiducial XS: 13 TeV results



2.31 +0.68/-0.60 (stat) +0.24/-0.20 (sys) fb measured (2.53 fb expected)







For 13 TeV data, 2 sets of preliminary results made public based on 2015 data and 2016 12.9 fb^{-1} separately

CMS-PAS-HIG-15-004 and CMS-PAS-HIG-16-033

We also contributed to ZZ->4l xs and Z->4l branching fraction measurements with 2015 dataset

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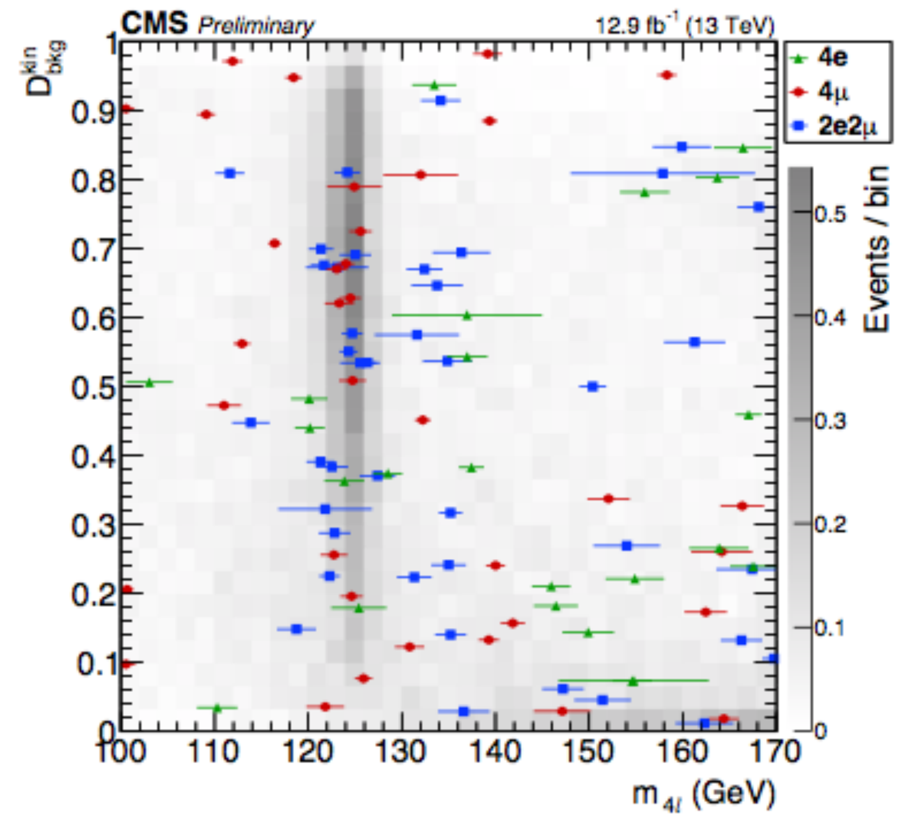
$$\mathcal{B}(Z \to \ell^+\ell^-\ell'^+\ell'^-) = 4.9^{+0.8}_{-0.7}\,(\text{stat})^{+0.3}_{-0.2}\,(\text{syst})^{+0.2}_{-0.1}\,(\text{theo}) \pm 0.1\,(\text{lumi}) \times 10^{-6}$$

Higgs mass measurement @ 13 TeV

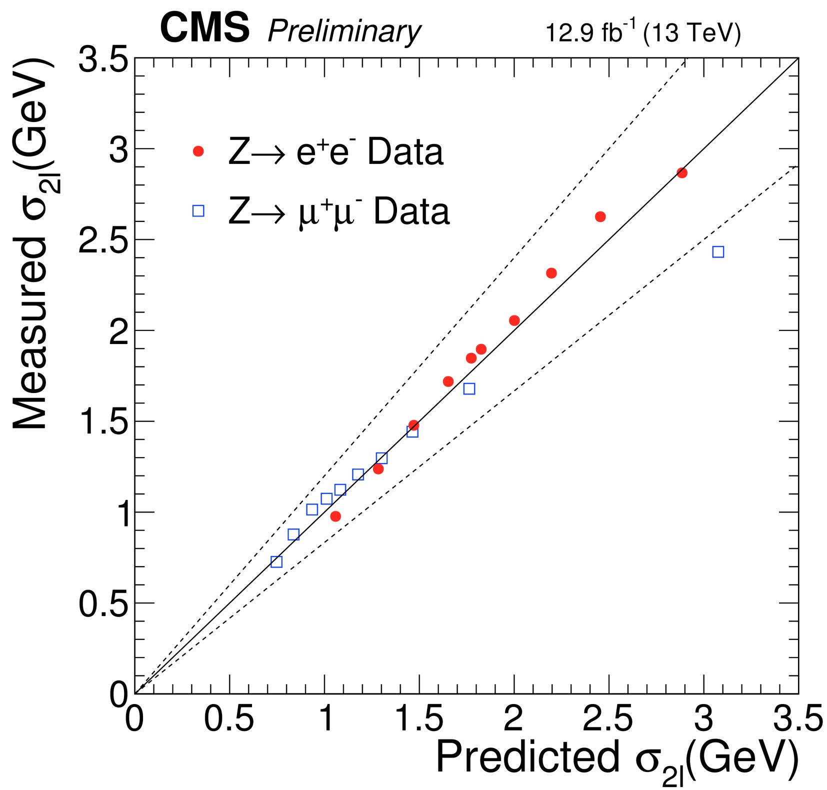
- Methodology follows Run I approach
- 3D observables to the statistical analysis
  - **m_{4l}**, kinematic discriminant $\boldsymbol{D_{bkg}^{kin}}$, per-event mass error $\boldsymbol{D_m}$



$$\mathcal{L}_{3D}^{m,\Gamma} \equiv \mathcal{L}_{3D}^{m,\Gamma}(m_{4\ell}, \mathcal{D}_{\rm m}, \mathcal{D}_{\rm bkg}^{\rm kin}) = \mathcal{P}(m_{4\ell}|m_{\rm H}, \Gamma, \mathcal{D}_{\rm m})\mathcal{P}(\mathcal{D}_{\rm m}|m_{4\ell}) \times \mathcal{P}(\mathcal{D}_{\rm bkg}^{\rm kin}|m_{4\ell})$$

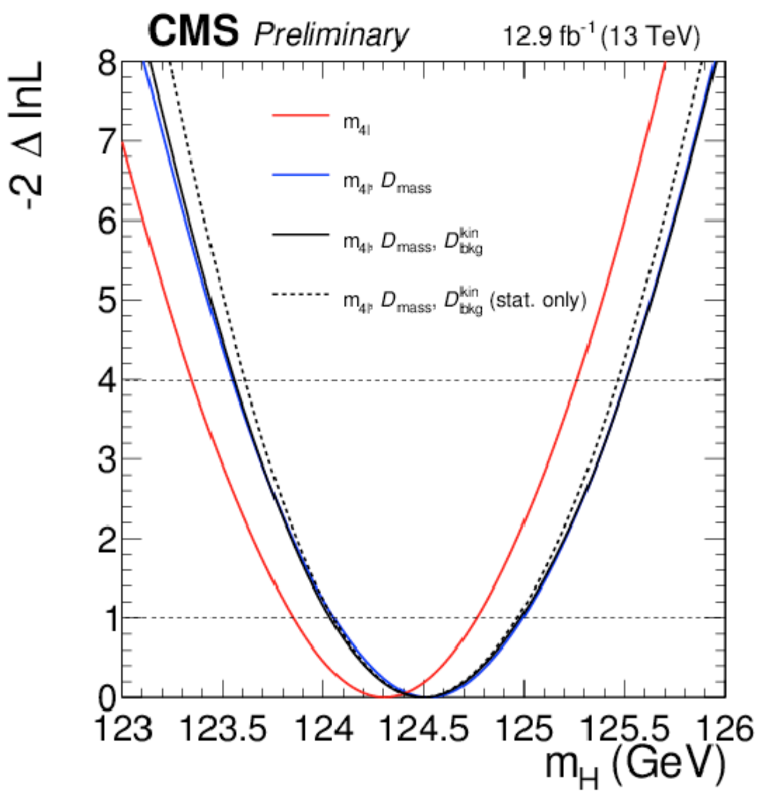
Correction of per-event mass error

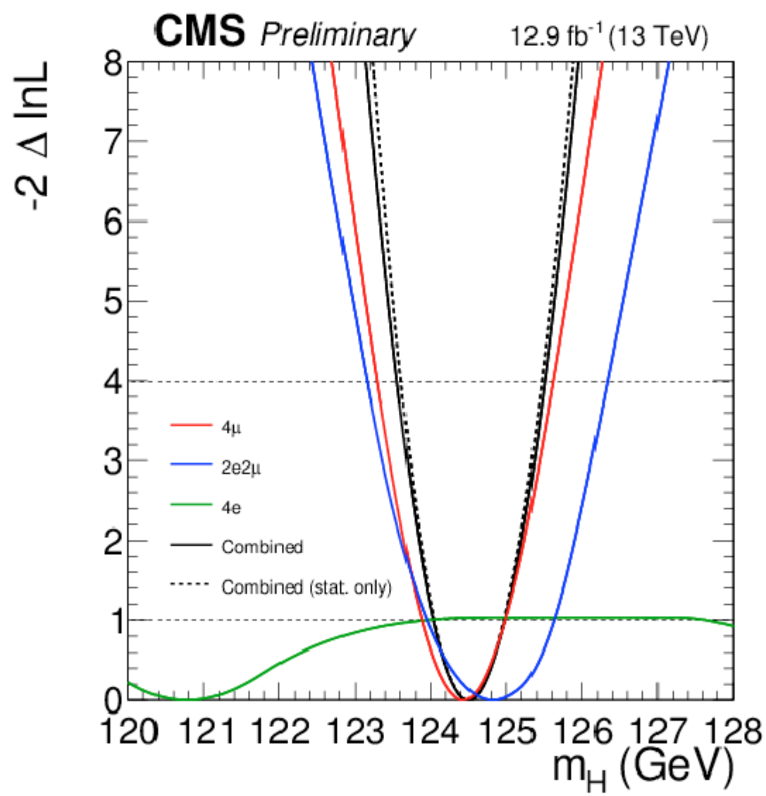
- Event by event mass error: lepton momentum error propagated to m4l
- Importan for mass measurement when statistics are limited



Comparison of measured mass resolution with the predicted dilepton mass resolution using the event-by-event mass uncertainty for $Z \to \ell\ell$ events in data. The dashed lines denote a ±20% region, used as the systematic uncertainty on the resolution.

Mass measurement results





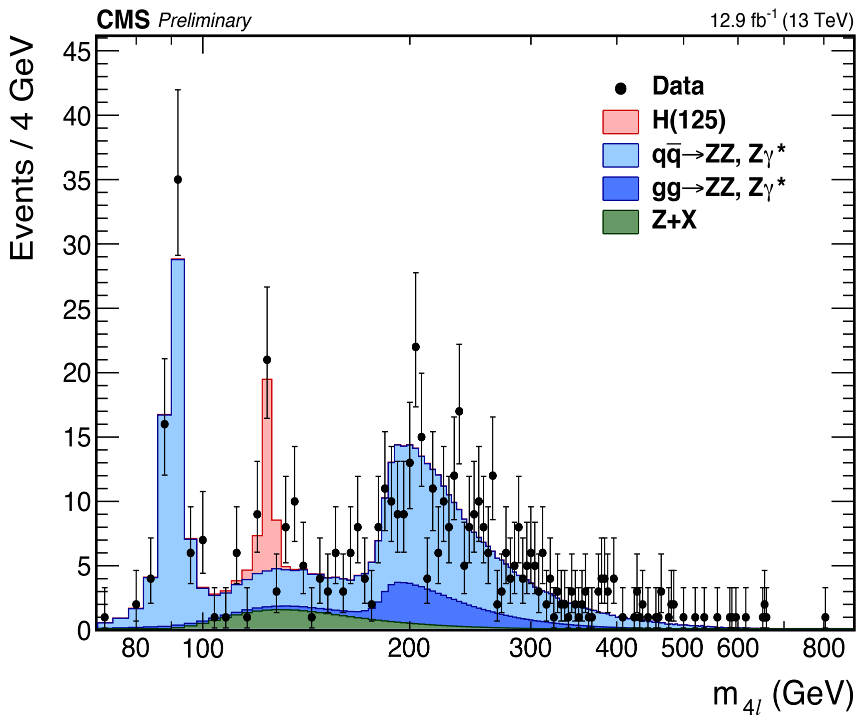
Channel	1D: $\mathcal{L}(m_{4l})$ (GeV)	2D: $\mathcal{L}(m_{4l}, \mathcal{D}_{\text{mass}})$ (GeV)	3D: $\mathcal{L}(m_{4l}, \mathcal{D}_{\text{mass}}, \mathcal{D}^{\text{kin}}_{\text{bkg}})$ (GeV)
4ℓ	$124.31^{+0.46}_{-0.45}$	$124.52^{+0.47}_{-0.47}$	$124.50^{+0.47}_{-0.45}(\text{stat.})^{+0.13}_{-0.11}(\text{sys.})$

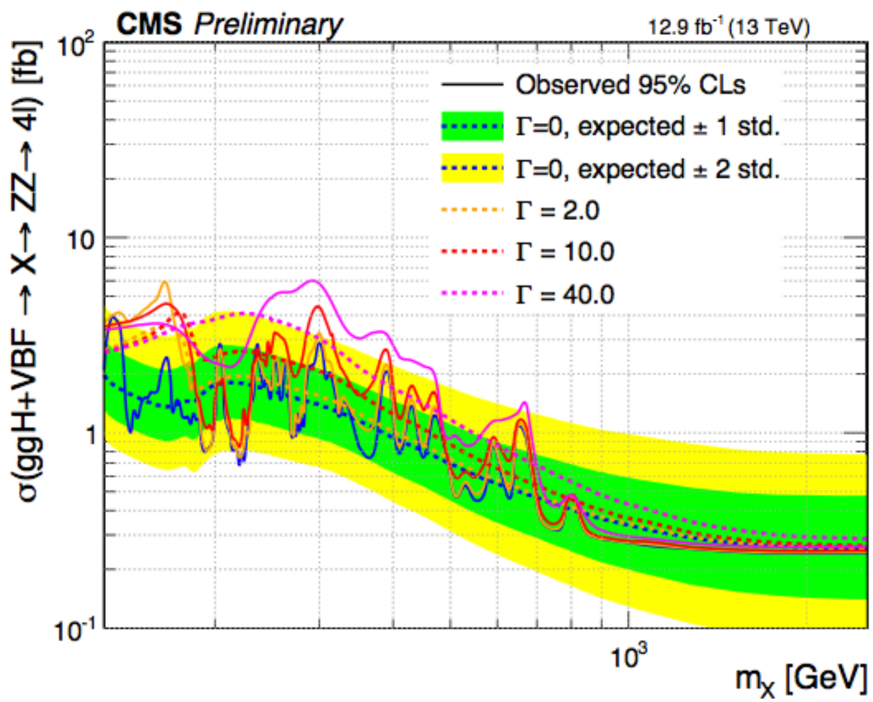
Heavy resonance searches

- Currently we are involved in all three ZZ final states
  - 4l: clean final state, but smallest branching ratio
    - best sensitivity for mass range < 500 GeV
  - 2l2q: largest branching ratio, but also huge backgrounds
    - better sensitivity for mass range > 1 TeV
  - 2l2v: relatively clean with modest branching ratio, but two neutrinos present in the final state
    - better sensitivity in the range from 500 GeV to 1 TeV

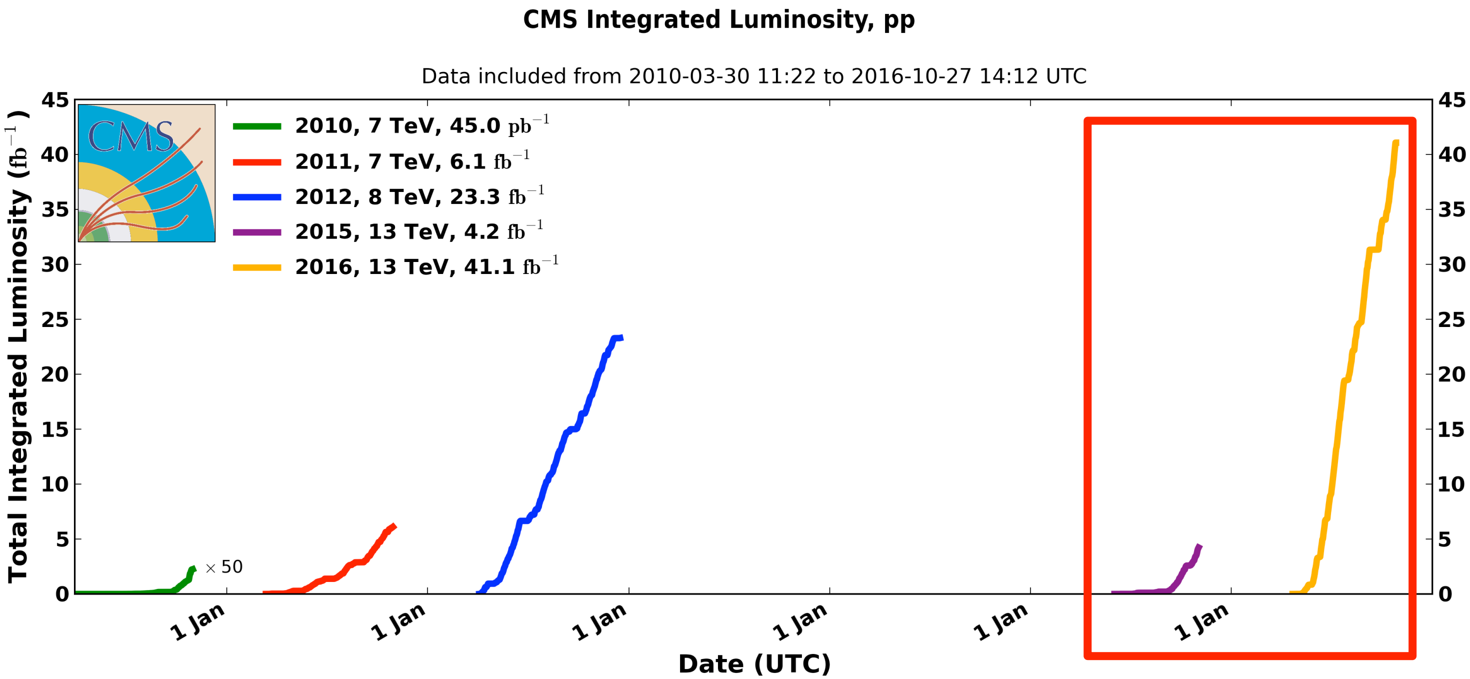
High mass resonance search

A general search for a scalar resonance with arbitrary mass and width





Plan



- Continue working on ZZ channel: both Higgs property measurement and new physics searches
- Several improvements in the pipeline for the papers with 2015+2016 full data
- Sensitivity study in 4l channel with Phase II simulation

back up

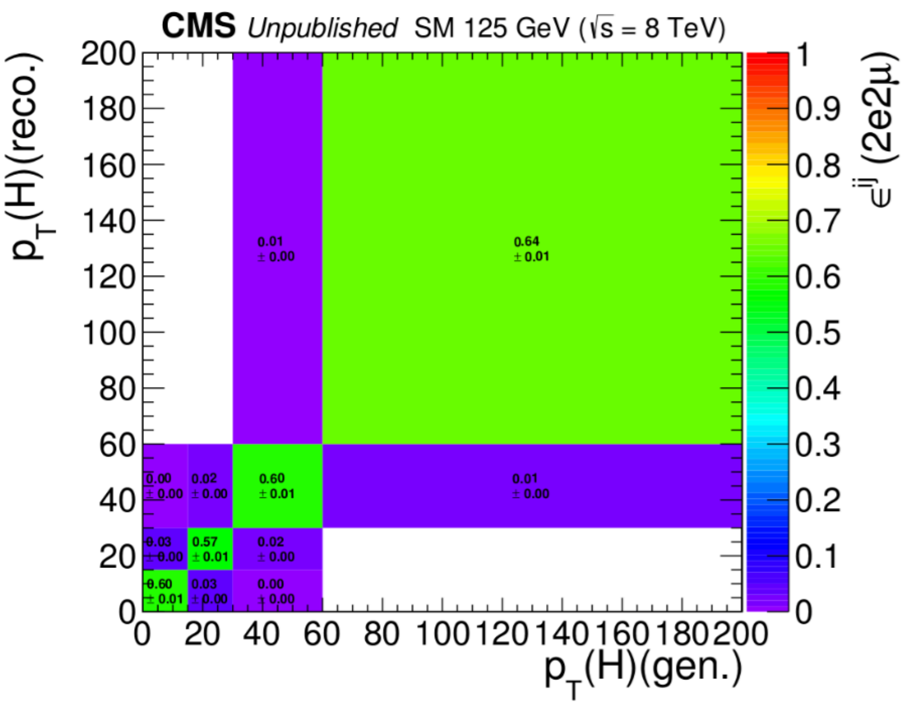
Fiducial XS: signal

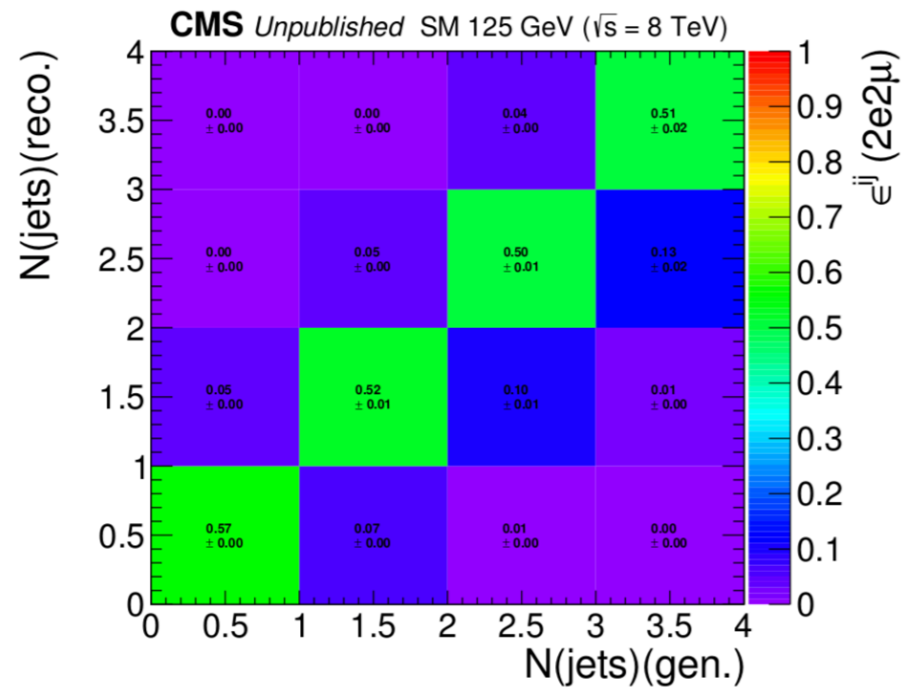
- The inclusive efficiency and non-fiducial ratios are determined from simulation → corrections derived from data are applied to the MC efficiencies
- Mild dependence on the production mode (~7%) of the factor $(1+f_{nonfid})\varepsilon$ is a result of the definition of the fiducial volume

Signal process	$\mathcal{A}_{\text{fid}}$	ϵ	f_{nonfid}	$(1+f_{\text{nonfid}})\epsilon$
Individual Higgs boson production modes				
$gg \to H$ (POWHEG+JHUGEN)	0.422 ± 0.001	0.647 ± 0.002	0.053 ± 0.001	0.681 ± 0.002
VBF (POWHEG)	0.476 ± 0.003	0.652 ± 0.005	0.040 ± 0.002	0.678 ± 0.005
WH (PYTHIA)	0.342 ± 0.002	0.627 ± 0.003	0.072 ± 0.002	0.672 ± 0.003
ZH (PYTHIA)	0.348 ± 0.003	0.634 ± 0.004	0.072 ± 0.003	0.679 ± 0.005
$t\bar{t}H$ (PYTHIA)	0.250 ± 0.003	0.601 ± 0.008	0.139 ± 0.008	0.685 ± 0.010
Some characteristic models of Higgs-like boson with exotic decays and properties				
$q\bar{q} \to H(J^{CP}=1^-)$ (JHUGEN)	0.238 ± 0.001	0.609 ± 0.002	0.054 ± 0.001	0.642 ± 0.002
$q\bar{q} \to H(J^{CP}=1^+)$ (JHUGEN)	0.283 ± 0.001	0.619 ± 0.002	0.051 ± 0.001	0.651 ± 0.002
$gg \to H \to Z\gamma^*$ (JHUGEN)	0.156 ± 0.001	0.622 ± 0.002	0.073 ± 0.001	0.667 ± 0.002
$gg \to H \to \gamma^*\gamma^*$ (JHUGEN)	0.188 ± 0.001	0.629 ± 0.002	0.066 ± 0.001	0.671 ± 0.002

$$
\begin{aligned}
N^{f,i}_{\text{obs}}(m_{4\ell}) &= N^{f,i}_{\text{fid}}(m_{4\ell}) + N^{f,i}_{\text{nonres}}(m_{4\ell}) + N^{f,i}_{\text{nonfid}}(m_{4\ell}) + N^{f,i}_{\text{bkg}}(m_{4\ell}) \\
&= \left(1 + f^{f,i}_{\text{nonfid}}\right) \cdot \sigma^{f,j}_{\text{fid}} \cdot \epsilon^{f}_{i,j} \cdot \mathcal{L} \cdot \mathcal{P}_{\text{res}}(m_{4\ell}) \\
&\quad + N^{f,i}_{\text{nonres}} \cdot \mathcal{P}_{\text{nonres}}(m_{4\ell}) + N^{f,i}_{\text{bkg}} \cdot \mathcal{P}_{\text{bkg}}(m_{4\ell}),
\end{aligned}
$$

Fiducial XS: differencial





- For differential measurements, the efficiency becomes a generalized **"detector response matrix"** (different for every model)
- The response matrix is included in the likelihood such that we directly fit for the fiducial cross section at fiducial level taking into account bin migration effects

Fiducial XS: systematic uncertainties

- Experimental systematic uncertainties mostly from Legacy paper:
  → Background estimation
    - QCD scale (~3% qqZZ, ~24% ggZZ) and PDF (~3% qqZZ, 7% ggZZ)
    - Reducible Background (20%-40%)

  → Lepton reconstruction efficiency (10% 4e, 4% 4mu)
  → Signal Shape
    - Lepton energy scale (0.3% 4e, 0.1% 4mu)
    - Lepton energy resolution (20%)

  → Non-resonant signal contribution
    - Effect on the final measurement is ~+4%/-11%

  → Integrated Luminosity (2.2% at 7 TeV, 2.6% at 8 TeV)

- For observables involving jets, Jet Energy Scale
  → Correlated across differential bins to preserve unity
  → 3%-12% for signal, 2%-16% for background

Fiducial XS: theory predictions

- ggH simulated with Powheg+JHUgen
  →NLO accuracy in QCD for 0-jets, interfaced to Pythia 6.4
  →Finite quark mass effects

- ggH simulated with Powheg+minloHJ
  →NLO accuracy in QCD for 0- and 1- jets, interfaced to Pythia 6.4
  →Finite quark mass effects

- ggH with HRes
  →NNLO in QCD + NNLL in resummation of soft gluon effects
  →Finite quark mass effects
  →Parton level generator, no interface to Pythia
  →Used to reweight Powheg+JHUgen+Pythia in a larger fiducial phase space
    - Plan to update reweighting to be at Powheg+JHUGen+Pythia level with Parton Shower but without Hadronization and UE (small effect)

- VBF simulated with Powheg

- WH, ZH, ttH simulated with Pythia 6.4

- All predictions normalized using cross section recommendations from the LHC Higgs Cross Section Working Group

Fiducial XS: theory uncertainties

- QCD scale and PDF/α_s uncertainties on ggH production computed bin-by-bin for each differential observable
  → for minloHJ and HRes, taking into account events with negative weights

- For VBF, WH, ZH, ttH QCD scale and PDF/α_s uncertainties taken as constant across bins and taken from LHCHXSWG

- PDF/α_s uncertainties correlated between VBF and VH, anti-correlated between ggH and ttH

- QCD scale uncertainties uncorrelated between production modes

- Uncertainty on acceptance (2%) and H → ZZ → 4ℓ branching ratio (2%) correlated across production modes

- For N(jets) measurement, use Stewart-Tackmann procedure

  $\Delta^2_N = \Delta^2_{\geq N} + \Delta^2_{\geq N+1}$ arxiv:1107.2117

2016 ICHEP H→ZZ→4l analysis

New results on the study of Higgs boson production in the four-lepton final state at $\sqrt{s} = 13$ TeV

M. Ahmad[1], N. Amapane[2], M. Bachtis[3], R. Bellan[2], R. Bhattacharya[4], C. Charlot[5], M. Chen[1], T. Cheng[1], R. Covarelli[2], B. Cox[6], S. Duric[7], L. Finco[2], A. Gritsan[8], B. Hirosky[6], M.B. Kiani[2], A. Korytov[9], M. Kovac[10], D. Lelas[10], H. Li[6], K. Long[7], C. Mariotti[11], J. McInerney[8], H. Mei[9], E. Migliore[2], P. Milenovic[9], V. Milosevic[12], G. Mitselmakher[9], C. Ochando[5], G. Ortona[5], P. Pigard[5], G. Petrucciani[3], G.L. Pinna Angioni[2], R. Plestina[1], D. Polic[10], I. Puljak[10], S. Regnard[5], P.M. Ribeiro Cipriano[10], H. Roskes[8], S. Roy Chowdhury[4], R. Salerno[5], U. Sarica[8], S. Sarkar[4], A. Savin[7], T. Sculac[5,10], Y. Sirois[5], N. Smith[7], D. Sperka[9], P. Traczyk[2], Y. Wang[6], N. Woods[7], M. Xiao[8], and C. You[8]

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[8] Johns Hopkins University
[9] University of Florida
[10] University of Split
[11] INFN Torino
[12] University of Belgrade

Run 1 SM-like Heavy Higgs